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Innovation and Application of High-altitude Inclined Fracture Tower Crane Repair Technology

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Abstract: *In cases of severe weather such as strong winds, tower cranes are prone to tilting and fracturing, presenting a pressing engineering challenge regarding their repair. Taking a specific engineering project as an example, this study investigates the characteristics of repairing high-altitude tilting and fractured tower cranes, focusing on reinforcement, dismantling, and reinstallation techniques. Ensuring the safety of dismantling operations for tilted and fractured tower cranes involves initial reinforcement techniques such as reverse tensioning with steel wire ropes, rigid steel connection reinforcement, and welding reinforcement of fractured steel plates. Subsequently, the construction details of the roof hoist steel structure foundation and its connection with reinforced concrete structures are clarified, followed by the dismantling of the tilted and fractured tower crane and the installation of a new tower crane. Utilizing BIM technology enables comprehensive simulation of the entire process of repairing high-altitude tilting and fractured tower cranes, facilitating the adoption of innovative approaches to address construction challenges, thereby achieving cost reduction and efficiency improvement objectives. Additionally, attention is drawn to key considerations during construction, providing valuable insights and references for future projects aimed at repairing tilted and fractured tower cranes.*

Keywords: *High-Rise Tower Cranes, Repair, Dismantling, Reinforcement, BIM*

1. Introduction

Construction tower cranes are sometimes affected by super typhoons, leading to tower crane tilting and posing a significant safety hazard, especially when some cranes remain precariously attached to buildings, posing a risk of collapse and potential falling. The crucial issue of how to dismantle and repair tilted tower cranes is of utmost importance. To ensure the safety of tower cranes, Zhou et al. [1] conducted numerical simulations to analyze and calculate the corresponding welding process parameters, recommending segmented welding, synchronous welding, and long weld seams. Jiang et al. [2] applied digital twin technology to assess the safety of tower crane lifting operations, highlighting tilted lifting as the most hazardous behavior. Ghazwani et al. [3] employed finite element techniques to analyze the stability of tower cranes under wind loads. For monitoring crane safety, Jiao et al. [4] utilized drone photography and image processing technologies for tower crane safety inspections. Lavrik et al. [5] proposed using automatic deposited gradient structure layers for repairing tower cranes. Han Hongmin [6] analyzed and addressed issues such as cracking in high tower crane counterweight support beams and below the rotary bearing. Wang Feng [7] examined the causes and corresponding solutions for cracks in tower crane mast belly bars. Ma Weikai [8] analyzed the forms of damage, causes, and solutions for the metal structures of crane bodies. Currently, there is minimal research on the dismantling and repair of tilted tower cranes. This paper addresses these issues in the context of a specific project, focusing on critical aspects such as crane positioning during lifting, reliable connections between crane bases and reinforced concrete, and reinforcement and dismantling of crane bodies.

2. Project Background

The project was impacted by the direct landfall of a super typhoon, with meteorological reports indicating typhoon wind speeds reaching level 14, averaging 45 m/s, and instantaneous gusts reaching up to 67.5 m/s when multiplied by a factor of 1.5. According to Table 20 in the "Code for Design of Cranes" [9], the calculated wind pressure for coastal design is 600~1000N/m2, and the calculated wind speed for

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design is 30~40m/s. During this typhoon landfall, the local wind levels and speeds at the tower crane site exceeded the design values specified in GB/T 3811-2008 "Crane Design Specification," resulting in a tipping accident involving one tower crane on the project site. Under the powerful wind pressures of the typhoon, the tower crane's mast experienced increased oscillation, leading to the fracture of the adjustment screws of the bottom second and third chord wall tie rods, as well as deformation of the tie rods. Additionally, two corner bolts of the bottom third chord wall standard section also fractured. Subsequently, the crane toppled and came to rest leaning against the parapet wall at the roof level of Building No. 9.

After thorough investigation and study of the tilted crane and its surroundings, it was decided to first reinforce the tilted tower crane. A method similar to the articulated boom tower crane used in the dismantling of super high-rise buildings was adopted to dismantle the tilted and fractured tower crane and eliminate the hazard. As shown in Figure 1, the construction process for repairing the high-altitude fractured and tilted tower crane is divided into reinforcement of the fractured and tilted tower crane, dismantling, and reinstallation.

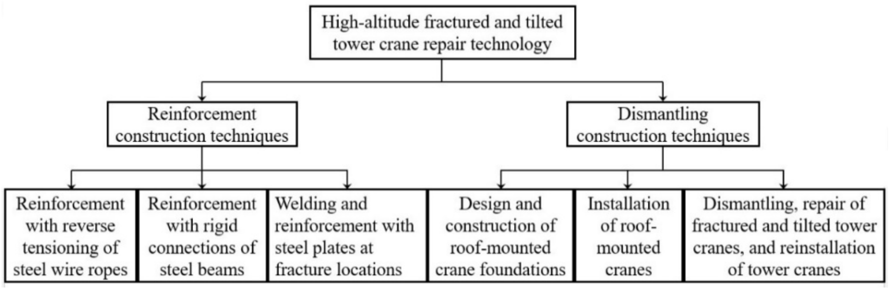

Figure 1: Tower Crane Repair Process

3. Tilted and Fractured Tower Crane Strengthening Construction Techniques

Due to the project's location in a coastal area and being in the peak season for typhoons, the tilted tower crane, attached to a shear wall, is at risk of falling at any time, posing significant safety hazards. In order to prevent the potential collapse of the tilted tower crane, which could threaten lives and property, and to ensure safety during dismantling, various reinforcement methods for the tilted and fractured tower crane were studied and discussed. It was decided to employ three methods simultaneously: reverse tensioning with steel wire ropes, rigid connection with steel sections, and welding steel plates at the fracture points of the crane. Among these methods, the reverse tensioning with steel wire ropes serves a protective function.

3.1 Reverse Tensioning with Steel Wire Ropes Reinforcement Technique

Starting from the upper floor adjacent to the tilting section of the crane, every two floors are secured using four Φ18 steel wire ropes for tensioning and fixing the tilted tower crane. During fixing, the steel wire ropes encircle the crane's standard sections and are secured using four rope clamps at both ends of the ropes (as shown in Figure 2). Each steel wire rope hangs a hand-operated hoist, with the other end of the hoist secured to a beam or shear wall on the floor. By tightening the steel wire ropes using the hand-operated hoist, the ends of the ropes form a figure-eight shape.

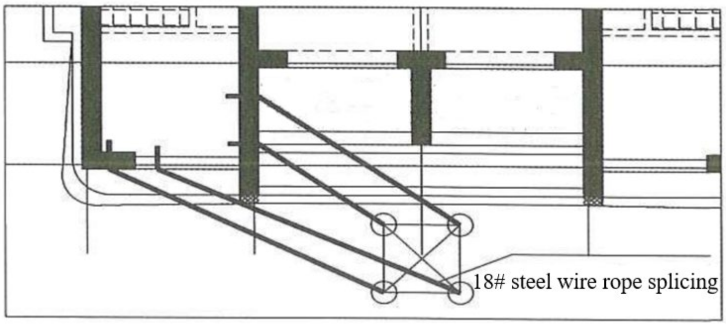

Figure 2: Schematic Diagram of Reverse Tensioning with Steel Wire Ropes Reinforcement Technique

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3.2 Steel Section Rigid Connection Reinforcement Technique

To prevent the tower crane from tilting again, it is necessary to start from the upper floor adjacent to the tilting section of the crane. Every other floor, at the shear wall position, a steel section fixing device is installed and securely welded to the crane's standard sections. Firstly, use No. 18 I-beams to encircle the crane's standard sections and weld them securely. Then, affix the No. 18 I-beam fixing device closely to the shear wall, installing fixing devices on floors 36, 38, 41, and 43 respectively. The fixing devices should be securely fixed at the shear wall positions, forming a "well" shape around the shear wall (as shown in Figure 3). To enhance stability, the bottom of the fixing devices should be supported and welded using No. 14 I-beams and steel pipes, ensuring the fixing devices are on the same horizontal plane as the standard sections.

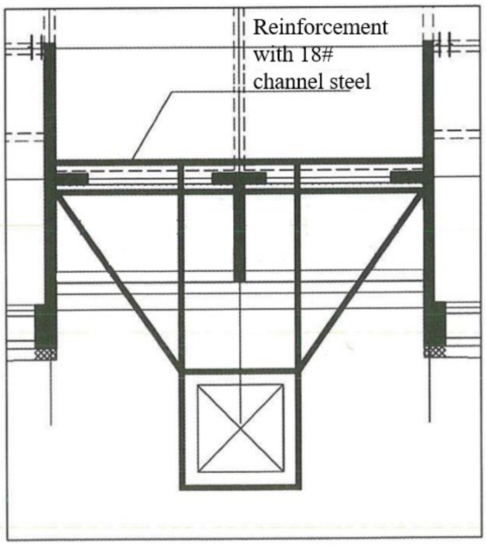

Figure 3: Schematic Diagram of Steel Section Rigid Connection Reinforcement Technique

3.3 Welding Reinforcement Technique for Fractured Steel Plates

As depicted in Figure 4, in order to prevent incidents such as bolt displacement at fracture points of 34F standard sections and instability of the base leading to overall sinking during dismantling, 20mm thick steel plates were welded at the openings of the junctions between two standard sections to reinforce the connection.

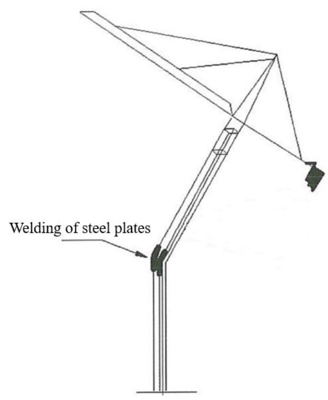

Figure 4: Welding reinforcement of fractured steel plates

4. Disassembly and Reinstallation Construction Techniques for Tilted Fractured Tower Cranes

4.1 Disassembly and Reinstallation Process for Tilted Fractured Tower Cranes

The specific process is as follows: reinforce the tower crane → construct a 3-ton roof crane foundation on the top of the building → manually install the 3-ton roof crane → use the 3-ton roof crane to construct a 6-ton roof crane foundation on the top of the building → use the 3-ton roof crane to install the 6-ton roof crane → use the 6-ton roof crane to construct a 25 ton roof crane foundation on the top of the building → use the 6-ton roof crane to install the 25 ton roof crane → use the 6-ton roof crane in conjunction with the 25 ton roof crane to remove the tilted tower crane → repair and restore the removed parts on the ground → use the self-lifting function of the non-tilted tower crane to reinstall the repaired parts → use the self-lifting function of the non-tilted tower crane to restore the tower crane to its original height → cooperate with the 6-ton roof crane Dismantling of 25 ton roof crane with tower crane → dismantling of 6-ton roof crane with 3-ton roof crane → dismantling of 3-ton roof crane with tower crane → removal of roof crane and auxiliary equipment.

4.2 Installation of Roof Hoists

In accordance with site conditions, transport of 3-ton roof hoist components to the roof is facilitated using a vertical construction elevator. The installation process for the 3-ton roof hoist proceeds as follows: foundation construction → erection of double-row return-type scaffolding → installation of rotating columns → installation of rotating bracket reels → installation of lifting splitters → installation of amplitude ropes → installation of lifting wire ropes → equipment trial and self-checking → inspection by testing authorities.

Upon completion of the 3-ton roof hoist installation, components for the 6-ton roof hoist are hoisted to the machinery room roof. The installation process for the 6-ton roof hoist includes: foundation construction → installation of cross-bottom frame → installation of rotating supports → installation of balance arms → installation of lifting winches and amplitude winches → installation of A-frame assembly → installation of lifting arms → installation of counterweights → equipment debugging and self-checking → inspection by testing authorities. During the ground assembly of the 6-ton roof hoist lifting arm, a 3-ton roof hoist is used to lift the lifting arm.

Upon completion of the 6-ton roof hoist installation, in coordination with the 3-ton roof hoist, components for the 25-ton roof hoist are hoisted to the roof. The installation process for the 25-ton roof hoist includes: foundation construction → installation of rotating supports and balance arm frames → installation of main hoist assembly and its amplitude mechanism assembly → installation of A-frame assembly → installation of counterweights → equipment debugging and self-checking → inspection by testing authorities. During the installation of the lifting arm, two parts of the lifting arm are assembled on the ground using a 50-ton mobile crane, then lifted to the roof using the 6-ton roof hoist, and assembled on the roof before installation.

Due to the thin roof panels and small beam sections, direct installation of roof hoists on the roof of high-rise residential buildings may lead to roof damage or cracking. Furthermore, the foundation of the roof hoists serves as the support structure for the standard sections and the entire tower body, bearing the primary load. Therefore, the key to whether roof hoists can be installed in high-rise residential buildings lies in the design of the roof hoist foundation.

To address the difficulty of installing roof hoists in high-rise residential buildings, this project employs double-spliced 40a I-beams as foundational supports, fixed along the direction of structural beams or shear walls (as shown in Figure 5). By arranging "T"-shaped or rectangular frameworks, the load on the roof hoist is transmitted along the shear walls or beams/columns to the pile foundation, meeting installation requirements. Additionally, through fixing devices, the roof hoist foundation is integrated with structural beams and walls, optimizing the connection method.

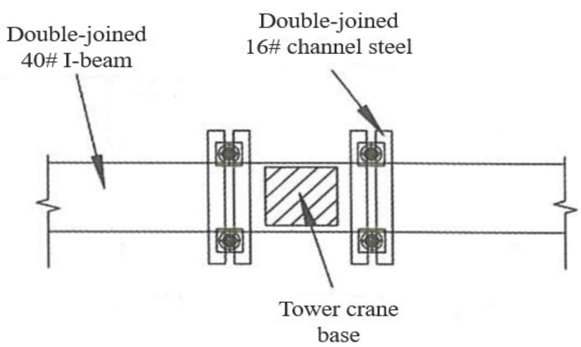

Figure 5: Plan View of Shear Wall Fixing Device

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4.3 Dismantling and Reinstallation of Tilted Tower Crane Components

In response to the tilted and fractured condition of the tower crane, on-site warning signs have been erected and personnel are stationed to prevent access to the dismantling area. The proposed dismantling procedure by the project team includes the following steps: initially dismantling the counterweights, followed by utilizing a 6-ton roof hoist in conjunction with a 25-ton roof hoist to dismantle the lifting arm, balance arm, and subsequently the rotating assembly and standard sections.

Dismantling of Counterweights: During the removal of counterweights, the 25-ton roof hoist stabilizes the balance point of the tower crane's front arm to prevent it from tilting downward after the counterweights are removed. The counterweights are dismantled using the 6-ton roof hoist; the TC6012 tower crane's counterweight composition is 6×2.4t+1.8t, with dismantling performed using the 6-ton roof hoist crane. Initially, the 1.8-ton counterweight is removed, followed by each 2.4-ton counterweight individually, with the final counterweight retained.

Dismantling of Lifting Arm and Balance Arm with Coordination of 6-ton and 25-ton Roof Hoists: During the dismantling of the lifting arm and balance arm, the counterweights are removed first. The 6-ton roof hoist supports the end of the balance arm, while the 25-ton roof hoist supports the balance point of the lifting arm. Two 5-ton manual hoists fixed on the roof are used to counter-pull and level the lifting arm until the connecting pins of the lifting arm can be easily removed. Subsequently, the lifting arm tie rods are dismantled and bundled together with the lifting arm. Next, two 200-meter-long hemp ropes are secured to the lifting arm, and the lifting arm is slowly lowered to the ground using the 25-ton roof hoist. After the lifting arm is dismantled, the end of the balance arm is secured with the 6-ton roof hoist. Four 8-meter steel cables are attached, with one end hanging from the balance arm's suspension point and the other end connected to two 5-ton manual hoists fixed on the 25-ton roof hoist. These manual hoists are used to level the balance arm slowly, and then the hook is carefully released to remove the restraint of the balance arm tie rod pin. Finally, the balance arm is slowly placed on the ground using the 25-ton roof hoist.

Dismantling of Rotating Assembly and Standard Sections using a 25-ton Roof Hoist: During the dismantling of the rotating assembly and standard sections, the tower top, rotation bearing, driver's cab, frame assembly, and three standard sections below the frame assembly are removed as a whole. A 28mm diameter steel wire rope is secured using a 25-ton roof hoist to the four main tie rods at the connection points between the tower top, balance arm, and lifting arm. The other end of the steel wire rope is attached to the 25-ton roof hoist, and the hook is slowly lifted to release the pin restraining the bolts between the sections to be dismantled and those that remain. Bolts securing the standard sections are removed. When removing the last two bolts of the standard sections, a 10mm diameter steel wire rope is first wrapped around both sections to prevent sudden tilting and potential hazards. After all bolts of the standard sections are completely removed, the wrapped steel wire rope is slowly relaxed to separate the sections. Subsequently, the dismantled tower top, rotation bearing, driver's cab, frame assembly, and three standard sections below the frame assembly are gently lowered to the ground using the 25-ton roof hoist.

Dismantling of Remaining Tilted Tower Sections: A 25-ton roof hoist is used to dismantle the remaining 12 sections of the tilted tower. Each standard section weighs 903 kilograms, making the total weight of the remaining 12 sections approximately 11.2 tons. The 25-ton roof hoist has a safe lifting capacity of 25 tons, thus allowing for the simultaneous dismantling and hoisting of the remaining 12 sections to the ground. Initially, a 28mm diameter steel wire rope is secured to the four main tie rods at the connection points where the dismantled standard sections were attached. The other end of the steel wire rope is connected to the 25-ton roof hoist. The hook is slowly lifted to release the pin restraining the bolts between the sections to be dismantled and those that remain. Bolts securing the standard sections are removed, and previous soft and hard reinforcements are released. After removing all bolts of the standard sections, a 10mm diameter steel wire rope is wrapped around both sections to prevent tilting and potential hazards during the removal process. Additionally, reinforcement cracks welded during the dismantling of the tilted tower sections are cut using gas welding. Finally, the wrapped steel wire rope is slowly relaxed to completely separate the sections. The dismantled remaining 12 sections of the tilted tower are then gently lowered to the ground using the 25-ton roof hoist.

Reinstallation of Tower Crane Post Inspection and Dismantling of Three Roof Hoists:After dismantling the tilted and fractured tower crane, professional inspection agencies are engaged to inspect and conduct magnetic particle testing on its components. Using a combination of a 25-ton roof hoist and a 6-ton roof hoist, the tower crane is reinstalled onto the highest undismantled standard section to restore functionality. Subsequently, the tower crane is dismantled in coordination with a 6-ton roof hoist,

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followed by dismantling with a 3-ton roof hoist. Finally, the tower crane itself is dismantled using a tower crane until all roof hoist foundations and auxiliary equipment are removed.

5. Repair BIM Construction Simulation of Tilted and Fractured Tower Crane

To facilitate construction more conveniently, quickly, and safely, Building Information Modeling (BIM) technology is employed for simulation and coordination regarding the reinforcement of roof hoist foundations, installation of roof hoists, and reinforcement and dismantling of the tilted and fractured tower crane [10]. Initially, a three-dimensional model is created using Revit software based on detailed drawings of roof hoist foundations to assess the feasibility of the plan and conduct visualized construction coordination. Subsequently, BIM simulations are performed for the installation of floor fixing devices, beam fixing devices, and shear wall fixing devices [11, 12]. Finally, the three-dimensional model established in Revit is imported into Navisworks software for simulation checks on operation space and installation sequence.

5.1 BIM Construction Simulation of Reinforcement for Tilted and Fractured Tower Crane

To reinforce the tilted and fractured tower crane, techniques such as reverse tensioning with steel wire ropes and rigid connection with structural steel are employed. During construction simulation and coordination, positions for manual hoists and structural steel are determined based on the actual tilted position of the crane. BIM technology is utilized to simulate and coordinate these reinforcement techniques. Firstly, the positions for manual hoists during each reverse tensioning with steel wire ropes are determined through the BIM model, and the required lengths of steel wire ropes are calculated. Corresponding two-dimensional drawings are generated for construction coordination. Secondly, the locations for structural steel reinforcement on the 36th, 38th, 41st, and 43rd floors are determined using the BIM model. The simulation reflects on-site conditions, quantities of structural steel are calculated, and two-dimensional drawings are generated for construction coordination.

5.2 BIM Construction Simulation of Dismantling Tilted and Fractured Tower Crane

Dismantling the tilted and fractured tower crane requires the coordinated use of 6-ton and 25-ton roof hoists. Navisworks software is utilized to simulate the dismantling steps and BIM models are employed for visualized construction coordination. Dismantling steps include: dismantling lifting wire ropes → dismantling counterweights → dismantling lifting arms → dismantling rotating assembly → dismantling tilted standard sections.

6. Key Technologies Summary

To effectively prevent further leaning and collapse of the tilted and fractured tower crane, reinforcement construction techniques were employed.

To address challenges posed by super tall buildings, large-span structures, unique architectural facades, and constrained construction sites, steel structure foundation beams were utilized for roof hoist bases. Additionally, post-construction, if tower cranes cannot be used for dismantling or rebuilding structures, fixed installations connect the roof hoist base with structural beams and walls, optimizing their connection. This approach effectively addresses issues related to thin reinforced concrete roof slabs or small beam cross-sections.

By coordinating the use of three roof hoists for dismantling the tilted and fractured tower crane, risks associated with high-altitude dismantling were significantly reduced. Within a month, hazardous conditions were successfully and efficiently eliminated, garnering praise from both owners and governmental entities.

The application of Building Information Modeling (BIM) technology enabled the pre-simulation of repairs for the tilted and fractured tower crane, thereby enhancing the feasibility of proposed solutions and reducing construction risks. Moreover, visualized construction coordination features strong instructional content, offering intuitive and concrete solutions to complex construction challenges.

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7. Conclusion

Through the analysis and application of repair technologies for high-altitude tilted and fractured tower cranes in actual engineering projects, along with corresponding BIM simulations, dismantling costs were reduced while efficiency was heightened. These advanced construction techniques serve as valuable references for future projects and hold significant potential for widespread adoption. The main conclusions drawn are as follows:

(1) The effectiveness of soft and hard tensioning reinforcement techniques in halting the progression of incidents, thereby enhancing crane stability during dismantling for ensured safety.

(2) The successful resolution of issues related to installing roof hoists on concrete structures through the transformation of roof hoist bases, optimizing connections between steel structure foundations and concrete structures to facilitate smooth installation.

(3) The substantial societal and environmental benefits derived from the coordinated use of three roof hoists for dismantling tilted and fractured tower cranes, effectively mitigating risks associated with high-altitude dismantling and efficiently eliminating hazardous conditions.

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